

GMRT Low Frequency Observations of Extrasolar Planetary Systems

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ABSTRACT

Extrasolar planets are expected to emit detectable low frequency radio emission. In this paper we present results from new low frequency observations of two extrasolar planetary systems (Epsilon Eridani and HD 128311) taken at 150 MHz with the Giant Metrewave Radio Telescope (GMRT). These two systems have been chosen because the stars are young (with ages < 1 Gyr) and are likely to have strong stellar winds, which will increase the expected radio flux. The planets are massive (presumably) gas giant planets in longer period orbits, and hence will not be tidally locked to their host star (as is likely to be the case for short period planets) and we would expect them to have a strong planetary dynamo and magnetic field. We do not detect either system, but are able to place tight upper limits on their low frequency radio emission, at levels comparable to the theoretical predictions for these systems. From these observations we have a 2.5σ limit of 7.8 mJy for ϵ Eri and 15.5 mJy for HD 128311. In addition, these upper limits also provide limits on the low frequency radio emission from the stars themselves. These results are discussed and also the prospects for the future detection of radio emission from extrasolar planets.

Key words: extrasolar planets – observations: radio

1 INTRODUCTION

The first definite extrasolar planet orbiting a normal star was detected in 1995 (Mayor & Queloz 1995). The main current techniques for detecting extrasolar planets (Doppler, transits etc) are indirect in nature, seeing the influence of the planet on the light from the host star rather than detecting the planetary properties directly. These methods infer rather limited information about the planet (such as the mass, or often just a lower limit on the mass). Observations at other wavelengths, such as low radio frequencies, have the potential for determining certain planetary properties that will be important in understanding planetary structure and evolution.

By analogy with the magnetic planets in the solar system, observations at radio wavelengths of extrasolar planets offers the (as yet unrealised) potential for a new way of directly detecting extrasolar planets and also a means of inferring information about the characteristics of the planets, such as the existence of a magnetosphere, the planetary magnetic field strength, planetary rotation and even the presence of moons, that may be difficult via other means (cf Higgins

et al. 1997), and which will be important in developing our understanding of how these planets form and evolve.

Low frequency radio observations of solar system planets have been made for decades (see, for example, Bastian et al. 2000). Burke & Franklin (1955) were the first to discover radio emission from Jupiter, which is an extremely bright and variable source at decametric (3–30 MHz) wavelengths. Due to ionospheric cut-off, it was not until the Voyager spacecraft era that the other solar system gas giant planets were detected (Broadfoot et al. 1981).

For solar system planets, the dominant mechanism for the low frequency radio emission is believed to be the electron cyclotron maser. The characteristic emission frequencies are determined by the magnetic field strength near the surface of the planet. The level of emission is dependent on local conditions (such as rotation and satellite interactions) but in essence all that is required is there to be a distribution of energetic electrons within the planetary magnetic field, with an anisotropy in velocity space and a large ratio of gyro to plasma frequencies.

We expect that massive extrasolar planets will, like Jupiter, have a dynamo driven magnetic field and a similar interaction with the wind of their host star. If this is the case then they will produce radio emission. All the larger planets in our own solar system produce radio emission, so there is

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no reason why we should not expect the same to occur for extrasolar planets (Ness et al. 1986). The major differences between extrasolar planets and solar system planets will be the sensitivity required to detect them and the frequencies at which the emission will occur (Stevens 2005).

The radio detection of extrasolar planets has been attempted several times, with a variety of different telescopes, at different frequencies. Winglee et al. (1986) used the Very Large Array (VLA) (at 0.33 GHz and 1.4 GHz) to observe six nearby stars, however no detections were made. Bastian et al. (2000) also used the VLA for multi-frequency observations of extrasolar planets at 1.4 GHz, 0.33 GHz and 74 MHz. No detections were reported, with sensitivities of ~ 50 mJy, at the lowest frequency used. More recently, the Ukrainian UTR-2 telescope has surveyed around 20 extrasolar planetary systems in the 10–25 MHz range, with a sensitivity of about 1.6 Jy. This survey produced no detections (Ryabov et al. 2003). Further to this Lazio & Farrell (2007) have observed τ Bootes with the VLA at 74 MHz. No detection was made, with an upper limit of around 150 mJy. Winterhalter et al. (2006) have used the GMRT to observe extrasolar planets, focusing on short period systems. The targets observed were τ Bootes, HD 162020, HD 179949, 70 Virginis and ν Andromedae. No detections were made.

In addition to these pointed observations, several large area radio surveys exist and these can provide constraints on the emission from extrasolar planets. These include the Cambridge 6C (150 MHz), 7C (150 MHz) and 8C (38 MHz) surveys and the VLA Low-Frequency Sky Survey (VLSS, 74 MHz). For details of these surveys see Hales et al. (1995) and Lazio et al. (2004).

There may be several reasons for these non-detections; insufficient sensitivity or incorrect (or even unlucky) target or frequency selection are probably key. We do not know how the radio emission from Jupiter-like planets really scales in other systems. There are also issues of beaming of the emission and time variability. Nonetheless, the prize of detecting extrasolar planets at radio wavelengths is sufficiently great to warrant continued searches.

The paper is organised as follows: in Section 2 we review our understanding of the expected radio emission from extrasolar planets. In Section 3 we introduce the GMRT targets and selection rationale. The data analysis and results are presented in Section 4, and in Section 5 we discuss the consequences and also briefly discuss limits from low-frequency observations.

2 LOW FREQUENCY PLANETARY RADIO EMISSION

Before we discuss extrasolar planetary radio emission, it will be useful to review the Jovian low frequency radio emission. Below a cut-off frequency of ~ 40 MHz, the Jovian radio emission is thought to be dominated by cyclotron-maser processes from keV electrons in the auroral regions of the planet. The power radiated by Jupiter at this frequency range is several hundred Gigawatts and below the cut-off frequency the radio power is comparable to that of the quiet Sun (Winterhalter et al. 2006). The emission is variable and solar events such as coronal mass ejections cause the emission intensity to increase. Apart from the solar wind con-

nection there is an additional component related to Io. The moon-planet interaction produces a significant increase in decametric emission (Gurnett et al. 2002). At higher (GHz) frequencies, synchrotron emission generated from the acceleration of energetic electrons, trapped in Jupiter’s magnetic field dominates the emission process. This means for detection of an extrasolar planet the intrinsic planetary emission will have to be much brighter than Jupiter. This can be achieved by the planet being in a shorter period orbit than Jupiter, or being more massive than Jupiter, or to be orbiting a star with a denser stellar wind than the Sun. The first two points have no impact on the radio flux of the star, but the third will. The stellar mass-loss rate \dot{M}_* will affect the planetary radio emission, and is related to the stellar luminosity L_x (Wood et al. 2002). From the scaling law for radio emission for extrasolar planets, we expect the planets observed here to be much more luminous than Jupiter, meaning their expected flux levels could be in the mJy range and potentially detectable (Stevens 2005).

Consequently, although Jupiter and the Sun can have comparable luminosities at low frequencies, for the brighter extrasolar planets, we expect the planets to be much brighter than their stellar hosts. This argument assumes constant sources, rather than flaring sources, and stellar flare activity may boost the stellar emission for short periods. In addition, it is believed that extrasolar planets will have a highly polarised emission (due to the emission process) whereas the level of polarisation for the stellar emission will vary considerably (Le Queau 1987).

Many extrasolar planets are in short period orbits, moving within the stellar corona of their host star, and we may expect some complicated magnetospheric geometries and interactions in such cases (Ip et al. 2004). On the other hand, any short period extrasolar planet may well be tidally locked, with a possible impact on the planetary dynamo (Grießmeier et al. 2004).

If we consider the case where the stellar wind is incident on the planetary magnetosphere then we can produce a scaling relationship relating the expected radio flux (P_r) of the planet to the local physical conditions (for a more detailed discussion see Stevens 2005, Lazio et al. 2004 and Zarka et al. 2001 and references therein), such that

$$P_r \propto \dot{M}_*^{2/3} V_w^{5/3} \mu_p^{2/3} A^{-4/3} D^{-2}, \quad (1)$$

where \dot{M}_* is the stellar mass-loss rate, V_w is the stellar wind velocity incident on the planetary magnetosphere, μ_p is the planetary magnetic moment, A is the orbital distance between the star and the planet, and D the distance to the Earth.

We might expect the planetary magnetic moment to roughly scale with the planetary mass. For the solar system, this relation is known as Blackett’s law (Blackett 1947). One form of Blackett’s law is $\mu_p \propto \omega M_p^{5/3}$, where μ_p is the planetary magnetic moment, M_p the planetary mass, and ω the planetary angular rotation frequency. There are other forms of this relationship, such that $\mu_p \propto M_p$ but in general the more massive the planet, the more massive will be the planetary magnetic moment, resulting in a larger magnetosphere and enhanced radio emission. Of course, these relations are based on the solar system and are not exact. We also have no

Table 1. The stellar and planetary orbital properties of the GMRT targets. The orbital data for the ϵ Eri system are from Benedict et al. (2006) and for HD 128311 from Vogt et al. (2005). For ϵ Eri b the inclination is known ($i = 30^\circ.1$), so that the planetary mass can be determined as $1.55 M_{Jup}$ (Benedict et al. 2006). The estimated stellar mass-loss rates are from Stevens (2005). The separation A is the star-planet separation at the time of the observations.

Name	Stellar Parameters			Planetary Parameters			
	Spectral type	Distance D (pc)	Mass-loss rate \dot{M}_* (M_\odot)	Orbital Eccentricity e	Orbital period P_{orb} (days)	Mass $M_p \sin i$ (M_{Jup})	Star-Planet Separation A (au)
ϵ Eri ϵ Eri b	K2V	3.22	17.4	0.70	2502	0.78	2.76
HD 128311	K0V	16.6	26.0				
HD 128311 b				0.25	458.6	2.18	1.04
HD 128311 c				0.17	928.3	3.21	1.70

evidence that they hold for exoplanetary systems but they allow us to make promising predictions.

3 TARGET SELECTION

Based on our knowledge of the situation in the solar system, the level of radio emission from a given magnetised extrasolar planet will be proportional to the stellar-wind ram-pressure flux incident on the planetary magnetosphere. This means that the expected level of radio emission from a given extrasolar planet will be a function of several factors, as expressed in eqn. (1).

The planetary period will greatly affect the level of stellar wind flux incident on the magnetosphere. Shorter period planets will be immersed in denser regions of the stellar wind. Although this compresses the magnetosphere, the net effect is to make the planet more radio luminous. Observations of extrasolar planets have focused on the short period systems, because from the scaling laws they are predicted to be the most luminous (potentially several thousand times more luminous than Jupiter). However, these systems have not been detected so far.

Planets that are close to their host star will experience tidal locking (Gri  meier et al. 2004). This may cause them to have a weak internal magnetic field and any dynamo action may be negligible, leading to a small magnetic moment, a reduced magnetosphere and consequently less radio emission. This is, of course, speculative and there is evidence for some magnetic activity associated with short period extrasolar planets which may indicate that even short period planets have some magnetic field (Shkolnik et al. 2003).

It is also useful to consider the stellar wind properties of the host star. Younger, X-ray bright stars, will have a stronger stellar wind than their older counterparts. From eqn. (1), we expect that the radio flux to scale as $\dot{M}_*^{2/3}$, and there will be an advantage to choosing planets around younger, more X-ray active stars. Stevens (2005) assumed that \dot{M}_* scaled linearly with X-ray luminosity (based on the work of Wood et al. 2002). The evidence for this scaling has weakened recently, and may well be weaker (for example, see Cranmer 2007 for a discussion of this).

3.1 The GMRT Targets

A number of previous searches have tended to focus on short period extrasolar planets, which from simple scaling laws are expected to be the most luminous (Winterhalter et al. 2006). In contrast, we have chosen to investigate longer period systems, since extrasolar planets which are particularly close to their host star might experience tidal locking (Gri  meier et al. 2004).

In the absence of any detections we do not know how the radio flux actually scales. The failure to detect short period systems means that the strategy of also observing longer period systems is perhaps prudent, just in case the short period systems turn out to be faint radio emitters. This strategy does have the disadvantage that the stellar wind density incident on the planetary magnetosphere declines sharply with orbital period. This effect is seen in our own solar system where planets with larger magnetic moments do not necessarily produce the most radio emission; Uranus has a larger magnetic moment than the Earth but produces less radio emission (Bergstr  h 1987).

Using the criteria discussed above we have selected 2 known extrasolar planetary systems to observe with the GMRT at 150 MHz; ϵ Eridani and HD 128311. Some of the relevant parameters of these systems are shown in Table 1, and the details of each system discussed below.

3.2 Epsilon Eridani

ϵ Eri is one of the nearest solar-type stars, at a distance of 3.22 pc. It is classified as K2V, and is slightly metal-poor ($\text{Fe}/\text{H} = -0.13 \pm 0.04$; Santos et al. 2004). Due to the high level of chromospheric activity observed radial velocity variations have been suspected as arising from the stellar activity cycle. ϵ Eri has been a target of many searches for planetary companions. Hubble Space Telescope astrometric observations have confirmed the presence of a planet (Benedict et al. 2006). ϵ Eri b is a moderately long period, highly eccentric extrasolar planet ($P_{orb} = 2502$ days, semi-major axis = 3.39 au, and $e = 0.70$). This planet is possibly not the only planetary companion in the ϵ Eri system. Observations in the infrared (using the IRAS satellite) have been used to suggest the presence of planets at large orbital radii (Quillen & Thorndike 2002). The debris disk that surround ϵ Eri suggest relative youth in the system (0.66 Gyr; Saffe et

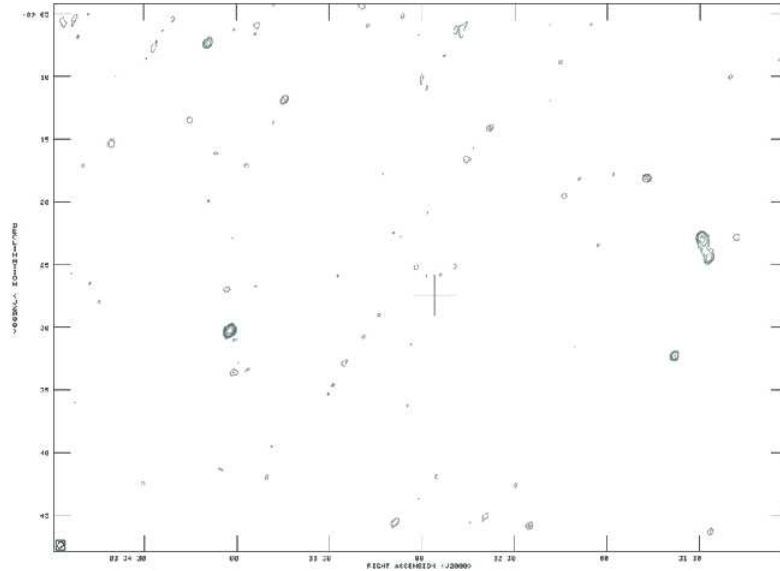


Figure 1. The 150 MHz view of the region around ϵ Eri (J2000.0 position marked with a cross). No emission is detected from ϵ Eri. The contours levels are 12.5, 25, 50, 100, 200, 400, 800 and 1600 mJy. The brightest source in the field is NVSS J033322-084803 ($\alpha = 03^h 33^m 22.80^s$, $\delta = -08^d 48^m 01.0^s$) with a flux of 2.85 Jy.

al. 2005). SCUBA measurements have suggested that there is a distributed ring, at an orbital radius of about 65 au, around ϵ Eri (Greaves et al. 1998) though there has been no clear evidence of a planet from optical observations. We concentrate on the planet discussed by Benedict et al. (2006).

ϵ Eri is an active star with an X-ray luminosity, of $L_X = 2.1 \times 10^{28} \text{ erg s}^{-1}$. According to the scaling of Wood et al. (2002) this results in an estimated mass-loss rate of $\dot{M}_* = 17\dot{M}_\odot$. This probably should be regarded as an upper limit, as recent work suggests a more gradual scaling with L_X (Cranmer 2007). The high eccentricity of ϵ Eri b means that the radio flux is predicted to change by a factor 3.5 over the course of the ~ 7 year orbit. The last periastron passage occurred at 2007.29 and the next apastron passage at 2010.71 (Benedict et al. 2006). Our observations were taken at 2006.8 which means that the star planet separation was equal to about 2.76 au. The inclination of the planet orbit is known ($i = 30^\circ.1 \pm 3^\circ.8$), which, combined with the radial velocity solution gives a planetary mass of $M_p = 1.55 \pm 0.24 M_{Jup}$.

3.3 HD 128311

HD 128311 is young (age of 0.5 – 1.0 Gyr) active K0 star (Vogt et al. 2005). HD 128311 is estimated to be 16.6 pc away from the Earth. It has an X-ray luminosity of $L_X = 3.0 \times 10^{28} \text{ erg s}^{-1}$ which results in an estimated mass-loss rate of $\dot{M}_* = 26\dot{M}_\odot$. There are two planets in orbit around HD 128311 with orbital periods of 458.6 and 928.3 days, with semi-major axes of 1.10 au and 1.76 au respectively (Vogt et al. 2005). These planets are quite eccentric and this has implications to the solar wind flux encountered. The effect will not be as pronounced as that in ϵ Eri b. Using the Vogt et al. (2005) orbital solution, the star-planet separation was about 1.04 au for HD 128311 b and 1.70 au for HD 128311 c at the time of observation.

4 DATA ANALYSIS AND RESULTS

The radio observations of ϵ Eri and HD 128311 were conducted with the GMRT, during cycle 11 on August 10-11 2006, for a duration of 4.13 hours each. The central frequency of the observation was 157.0 MHz and a bandwidth of 8 MHz was used. For ϵ Eri, 3C48 was used as the flux calibration and 0114–211 was used as the phase calibration with a time on source in a single scan of 30 minutes before moving to the phase calibration for 5 minutes. For HD 128311, 3C286 was used for flux calibration and 1419+064 was used as the phase calibration, the same procedure as for ϵ Eri was followed.

The data was calibrated using standard procedures in AIPS (Astronomical Image Processing System). Unfortunately at this frequency, the data is significantly affected by RFI, which was identified and excised manually using AIPS procedures. Wide field mapping with 5 degree diameter (close to full width of the beam) consisting of 121 facets were performed to correct for curvature of the sky. Several iterations of phase-only self calibration was applied to correct for short term phase changes. After phase-only self calibration has converged, one round of amplitude and phase self calibration was carried out. The 121 facets were then combined to make one final image. The final restoring beam (resolution) is $32.1'' \times 23.2''$ for ϵ Eri and $45.4'' \times 30.6''$ for HD 128311. While these stars have substantial proper motions ($\sim 1000 \text{ mas/yr}$ for ϵ Eri, and 320 mas/yr for HD 128311, Perryman et al. 1997), this has no impact on the astrometry of these observations.

4.1 Results and Flux Limits

In the full field of view (of area $\sim 10^\circ \times 10^\circ$) for both the ϵ Eri and HD 128311 fields we have detected a large number of sources. For the two observations the RMS noise levels are $\sigma = 3.16 \text{ mJy}$ (ϵ Eri) and $\sigma = 6.20 \text{ mJy}$ (HD 128311). We de-

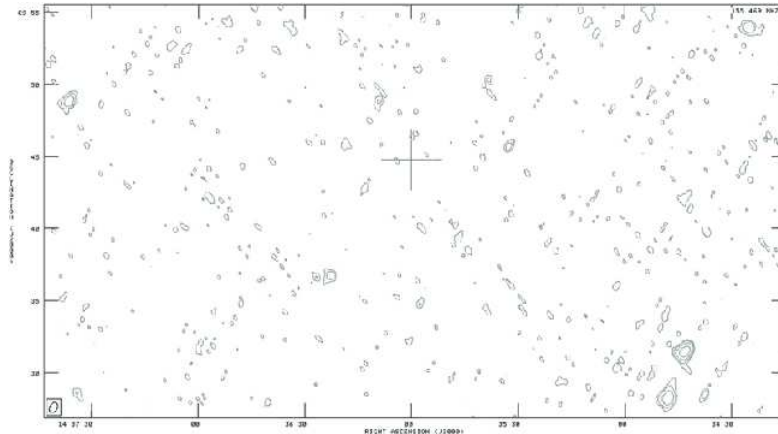


Figure 2. The 150 MHz view of the region around HD 128311 (J2000.0 position marked with a cross). No emission is detected from HD 128311. The contours levels are 25, 50, 100, 200 and 400 mJy. The brightest source in the field is TXS 1432+07 ($\alpha = 14^h 34^m 43.25^s$, $\delta = -09^d 32^m 45.64^s$) with a flux of 0.45 Jy.

fine a source as one that has a flux of at least 5σ . In the ϵ Eri field, a total of 571 sources were detected with flux levels between 16 mJy and 2.85 Jy. For HD 128311 the corresponding numbers are 297 sources, with fluxes between 30 mJy and 0.45 Jy. These sources are most likely to be background AGN but at 150 MHz one might expect to detect the presence of a starburst galaxy population, as starburst galaxies have a steeper spectrum than many AGN. Moss et al. (2007) have used the GMRT to undertake a 610 MHz survey to detect such objects. We expect that lower frequency observations will assist in the detection of these sources and this will be discussed elsewhere (George, in prep). Images of the smaller regions around ϵ Eri and HD 128311 are shown in Fig. 1 and Fig. 2 respectively. The locations of ϵ Eri and HD 128311 are marked with crosses in the respective diagrams.

In Fig. 1, there are two bright sources in the vicinity of ϵ Eri. These are NVSS J033322-084803 ($\alpha = 03^h 33^m 22.80^s$, $\delta = -08^d 48^m 01.0^s$), which has a 150 MHz flux of 2.85 Jy, and PMN J0331-0923 ($\alpha = 03^h 31^m 25.8^s$, $\delta = -09^d 23^m 58^s$) which is a double lobed source.

In Fig. 2, the brightest source is at $\alpha = 14^h 34^m 43.25^s$, $\delta = -09^d 32^m 45.64^s$, most likely TXS 1432+07, and has a 150 MHz flux of 0.45 Jy.

It is clear from both Fig. 1 and Fig. 2 that neither target source has been detected at 150 MHz, and we focus on the upper limits on the radio emission that can be derived from these observations. We have adopted the same approaches as Lazio & Farrell (2007) to derive the flux limits for the extrasolar planets. We take two different approaches to calculating the flux limit for each source. The first estimate is from the RMS noise level (σ) for each observation, and we adopt the flux upper limit of 2.5σ . Using this method we have a flux limit of 7.9 mJy for ϵ Eri and 15.5 mJy for HD 128311. We also use the brightest pixel within a beam centered on the targets to estimate the flux density of any possible radio emission and allows us to take into account the background level determined by the mean brightness in a region surrounding the central beam. We determine upper limits via this method of 13.8 mJy for ϵ Eri and 19.4 mJy for HD 12811. These upper limits are summarised in Table 2.

Table 2. The derived flux limits for the extrasolar planetary systems observed with the GMRT at 150 MHz.

Planet Name	Flux limit (2.5σ) (mJy)	Brightest Pixel (mJy)
ϵ Eri b	7.9	13.8
HD 128311 b	15.5	19.4

5 DISCUSSION

These GMRT observations have provided tight upper limits on the 150 MHz flux from two nearby, longer period extrasolar planets. In addition to these observations we can also add in VLSS 74 MHz limits for these two objects. For ϵ Eri this is approximately 0.9 Jy and 1.2 Jy for HD 128311. Previous searches for extrasolar planets have focused on short period systems, but have also failed to detect anything. These observations complement and extend the range of extrasolar planetary systems that have been surveyed.

Our observations do not quite reach the expected radio flux of these systems. Stevens (2005) suggests that the mean radio flux for ϵ Eri b would be 2.4 mJy and 1.4 mJy for HD 128311 b, of course these are only mean values and do not take account for the eccentricity of the system. In both cases we have observed the planet closer than at its mean position so we would expect the flux to increase. Our flux limits do approach these values. There are several reasons why we have not detected these systems.

(i) Insufficient sensitivity: One issue for longer period systems is that they are predicted to be intrinsically fainter than the shorter period systems, with the expected flux falling off as $P_{orb}^{-8/9}$ (all other things being equal). Clearly more sensitive observations are required.

(ii) Wrong frequency: The radio cut-off for Jupiter is around 40 MHz, and it could be the case that 150 MHz is too high a frequency to detect the electron-cyclotron maser emission. The Jovian cut-off is determined by the magnetic field strength near the planetary surface, and probably scales roughly linearly with planetary mass. Consequently, we might expect to only detect planets with a mass

of $M_p \geq 3.8M_{Jup}$. The mass of ϵ Eri b ($M_p = 1.55M_{Jup}$) is well constrained and is below this value. For HD 128311, we have only lower limits for the planetary masses (of 2.2 and $3.2M_{Jup}$). If the system inclination is less than $\sim 60^\circ$ then one of the planets will have a mass greater than this limit and if $i < 35^\circ$ (and the planets are co-planar) then both will exceed this limit. While not guaranteed, there is a moderate chance that 150 MHz is an appropriate frequency for detection. Clearly, simultaneous observations in a much wider frequency range is desirable, particularly at lower frequencies.

(iii) Wrong planetary orientation: In the case of the solar system planets the low frequency emission comes from a hollow cone with a wide opening angle ($\sim 75^\circ$ half-width opening angle for Jupiter). For Jupiter the emission has an equivalent solid angle of 1.6 sterad (Zarka & Cecconi 2004). Assuming this also applies to extrasolar planets then we would expect to see emission from a given extrasolar planet at some epoch. However, this does raise the related issue of time variability. It could be that we simply observed the systems at the wrong time.

To solve the problem of detecting the magnetospheric emission from extrasolar planets we can look forward to the Low Frequency Array (LOFAR). LOFAR is expected to operate in the frequency range of 10-240 MHz. The design goals suggest that a sensitivity, in a 15 minute integration with a 4 MHz bandwidth, of around 2 mJy will be possible. Several features of LOFAR make it a highly capable instrument for detecting extrasolar planets –first, it has an appropriate frequency coverage, second it is more sensitive than current telescopes and thirdly its design means that it can survey large portions of the sky. In spite of our theoretical prejudices, we really do not know which extrasolar planetary systems will turn out to be brightest, and the wide field capability of LOFAR will be more productive than the repeated pointed observations that have hitherto been done. We expect that extrasolar planetary radio emission will be detectable with LOFAR and comparable arrays, if produced in a manner similar to the solar system planets.

In summary, we have presented GMRT observations of two extrasolar planetary systems (ϵ Eri and HD 128311) at 150 MHz. We have not detected either systems, but have provided tight upper limits on the low-frequency radio emission from the magnetospheres of these planets.

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